Influence of Microphysical Cloud Parameterizations on Microwave Brightness Temperatures

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***Abstract*—The microphysical parameterization of clouds and rain cells plays a central role in atmospheric forward radiative transfer models used in calculating microwave brightness temperatures. The absorption and scattering properties of a hydrometeor-laden atmosphere are governed by particle phase, size distribution, aggregate density, shape, and dielectric constant. This study investigates the sensitivity of brightness temperatures with respect to the microphysical cloud parameterization. Calculated wideband (6–410 GHz) brightness temperatures were studied for four evolutionary stages of an oceanic convective storm using a five-phase hydrometeor model in a planar-stratified scattering-based radiative transfer model. Five other microphysical cloud parameterizations were compared to the baseline calculations to evaluate brightness temperature sensitivity to gross changes in the hydrometeor size distributions and the ice–air–water ratios in the frozen or partly frozen phase. The comparison shows that enlarging the raindrop size or adding water to the partly frozen hydrometeor mix warms brightness temperatures by as much as 55 K at 6 GHz. The cooling signature caused by ice scattering intensifies with increasing ice concentrations and at higher frequencies. An additional comparison to measured Convection and Moisture Experiment (CAMEX-3) brightness temperatures shows that in general all but two parameterizations produce calculated T_Bs that fall within the CAMEX-3 observed minima and maxima. The exceptions are for parameterizations that enhance the scattering characteristics of frozen hydrometeors.**

***Index Terms*—Clouds, electromagnetic scattering, millimeter wave radiometry, rain, remote sensing, snow.**

I. Introduction

OVER the past four decades, significant effort has been devoted to understanding the microphysical cloud characteristics of convective storms (e.g., [1]–[3]). The microphysics of clouds is of considerable interest in a wide range of interdisciplinary studies. These studies include improving global climate models for understanding climate variability, investigating the role of hydrometeors in lightning generation, examining chemical interactions and rain evolution in clouds for pollution research, studying radar and lidar remote sensing applications, and developing precipitation parameter retrievals from satellite-based passive microwave imagery.

Of interest here is improving our understanding of the relationships between the microphysics of hydrometeors in a convective storm and the upwelling microwave brightness temperatures for the purposes of rain rate and precipitation parameter retrieval. A comprehensive understanding of these relationships is hindered by the lack of accurate and sufficiently detailed atmospheric microphysical profile truth [4], [5]. Difficulties in obtaining microphysical cloud profile truth for convective systems stem from limitations in remotely sensed measurements, aircraft sampling capabilities, and the extremely inhomogeneous and complex nature of convection [6], [7]. The dynamics of convection complicate the *in situ* measurements of hydrometeor size, shape, total water content and the ice–air–water ratio, and Nyquist spatial and temporal sampling of these quantities remains a formidable challenge.

A microphysical cloud parameterization used in radiative transfer models requires specifying the size distributions and ice–air–water ratios for each hydrometeor type at each atmospheric level along with vertical profiles of temperature, relative humidity, and pressure. Parameterizations have been developed using statistics from physical models of particle growth and coalescence as well as knowledge from limited *in situ*, radar, and lidar observations. Early cloud parameterizations (e.g., [8]) used in radiative transfer models allowed for a uniform rain layer and separate cloud water layer with no ice particles. Later models added an ice layer (e.g., [9]–[12]).

Contemporary microphysical cloud parameterizations allow for multiple liquid and ice phases (e.g., [2], [4], [13], [14]). Several research studies have indicated that five hydrometeor phases adequately represent a convective storm [5], [15] from the standpoint of passive microwave signatures. The five hydrometeor phases are generally classified as cloud water, rain drops, cloud ice, snow (or ice aggregates), and graupel (including hail). The rain drops are commonly modeled by the Marshall–Palmer (MP) [16] size distribution. However there appear to be no universally accepted size distribution parameterizations or ice–air–water ratios for the other four hydrometeor types [6]. In general, the microphysical parameterizations used by radiative transfer modelers are appropriate for only specific storm occurrences.

As satellite passive microwave sensing of rain rate and other precipitation parameters (e.g., cell top altitude, see [17]) matures, it is important to understand the impact of the various common hydrometeor parameterizations on the upwelling microwave brightness. Accordingly, the purpose of this work is to study the sensitivity of computed microwave brightness temperatures to changes in the microphysical parameters. The analysis of these changes is facilitated using wideband microwave aircraft data. Since identifying the best parameterization requires detailed collocated and coincident *in situ*, radar, and radiometer observations, we instead focus on identifying a plausible class of parameterizations. Indeed, cloud parameterizations are case specific. The work of [18] and [19] are two examples where parameterizations that best match case-specific radiometer observations have been determined. Even though an optimal parameterization cannot be identified in this study, inappropriate and unrealistic parameterizations can be identified and avoided in future work.

In studying microphysical cloud parameterizations and their effect on computed brightness temperatures, a planar-stratified atmosphere and a midlatitude oceanic surface are assumed. The simple planar model is adequate for all but the most localized cumuluform convection. The highly reflective oceanic background is more uniform and provides greater sensitivity to hydrometeor scattering and absorption than would a land background, and thus represents the more conservative of the two backgrounds. For comparison purposes, four cloud profiles are selected to represent the early cumulus, evolving, mature, and dissipating stages of a convective storm. Six microphysical cloud parameterizations were selected for use in evaluating brightness temperature sensitivities to the hydrometeor size parameters, and frozen particle ice–air–water ratios. A five-hydrometeor-phase (cloud water, rain, cloud ice, dry snow, and dry graupel) parameterization is considered to be the baseline case. Brightness temperatures at twelve frequencies (6.0, 10.69, 18.7, 23.8, 36.5, 89.0, 150.0, 183.31 + 7.0, 220.0, 325 + 8.0, 340.0, and 410.0 GHz) were computed for each of the four cloud stages and six parameterizations using the planar-stratified scattering-based radiative transfer model of [11]. We discuss herein the variations in brightness temperature values when the microphysical cloud parameterization is changed in the radiative transfer calculations.

While convective storms under different prevailing conditions (e.g., tropical, midlatitude, maritime, or continental) have differing hydrometeor characteristics, this study nonetheless identifies several issues. First, in order to select the proper parameterization for any specific condition, one requires a set of detailed atmospheric truth profiles along with a collocated and coincident set of brightness temperature observations. Second, we show the sensitive relationship between the brightness temperature and the underlying hydrometeor profile. In identifying these issues we first briefly describe the radiative transfer model and calculations, including the ocean surface and top-of-atmosphere conditions. Dielectric mixing theory for heterogeneous snow and graupel particles is outlined. Section III details the six microphysical cloud parameterizations. The comparison among the six parameterizations (Section IV) and to the aircraft data (Section V) is described with a summary in Section VI.

VI. Summary

Brightness temperatures at twelve frequencies between 6.0 and 410.0 GHz were computed for four storm stages obtained from the simulated GCE model set of [36]. The four profiles used in the comparison represent a convective storm in its early cumulus, evolving, mature, and dissipating stages. The investigation illustrates how specific microphysical cloud parameterizations can affect oceanic microwave brightness temperatures.

The densities of the five hydrometeor types of the GCE data were mapped into six different microphysical cloud parameterizations. The parameterizations were designed to evaluate brightness temperature sensitivity to particle size distributions and ice–air–water ratios. A comparison among the six parameterizations, four convective storm stages, and twelve frequencies was performed. A five hydrometeor-phase parameterization [2], [13] was considered as the baseline case.

The comparisons generally showed that increasing the emphasis of water or rain warmed the brightness temperatures. When the size distribution of rain was changed to that of the Joss *et al.* thunderstorm size distribution (which favors larger particle diameters), the T_B values at 6 GHz were warmed by up to 55 K. At 18 and 23.8 GHz the larger-sized Joss particles initiate liquid scattering more so than the smaller-sized MP size distribution, resulting in a small T_B cooling. From 10.69 GHz to 36.5 GHz, a transition from mostly absorptive (characterized by warmer T_B values) to mostly scattering (characterized by cooler T_B values) occurs. At stage C (the early cumulus profile), a change from having the coolest T_B at 10.69 GHz for all parameterizations and pixels (because there is little absorptive warming) to having the warmest T_B values at 36.5 GHz (because there is little scattering) occurs. Above 36.5 GHz changes in the raindrop size distribution initiated no differences in the T_B values with respect to the five-phase model due to the strong scattering signatures of storm-top ice at these higher frequencies. Adding liquid water to the snow and graupel hydrometeors caused absorptive warming at the low and middle frequencies.

From 89 GHz to 220 GHz the scattering signature is stronger than the absorptive warming signature. The comparison showed that the cooling signature due to ice scattering at higher frequencies was increased with larger ice concentrations. The ice concentration rose when additional ice was allocated to the ice–air–water ratio. Above 220 GHz the T_B variability among all six parameterizations and four stages was reduced. The compression was caused by an increasing sensitivity to hydrometeor size as wavelength decreased. This increasing sensitivity caused an increased opacity at the higher frequencies.

Finally, a comparison of the calculated T_B values with available observed T_B values from the CAMEX-3 experiment showed reasonable agreement for most stages and parameterizations. Exceptions occurred for the doubled ice-ratio parameterization and the two-phase parameterization. These two parameterizations consistently yielded T_B values outside the range of the observed minima and maxima, indicating that they are less physically realistic than the others. Another interesting feature is that the 220 and 340 GHz T_B calculations are well within the minima and maxima of the observations, thus providing an argument for increasing the diversity and complexity of frozen hydrometeors in models of convective cloud profiles. (The parameterizations used herein do not provide enough diversity at these frequencies.) Finally, there are a few stages/parameterizations/frequencies whose calculations do not fall within the observed minima and maxima. These few inconsistent cases could mean that the clouds were inadequately categorized into cumulus, evolving, mature, and/or dissipating stages or that the parameterizations are not modeling the true cloud microphysics for all cases. A detailed coincident set of T_B observations and *in situ* PSD measurements might be used to further refine cloud microphysical parameterizations.